Parallel Computing
Slides from Prof. Jeffrey Hollingsworth

What is Parallel Computing?

- Does it include:
  - super-scalar processing (more than one instruction at once)?
  - client/server computing?
    - what if RPC calls are non-blocking?
  - vector processing (same instruction to several values)?
  - collection of PC's **not** connected to a network?

- For us, parallel computing requires:
  - more than one processing element
  - nodes connected to a communication network
  - nodes working together to solve a single problem

Why Parallelism

- Speed
  - need to get results faster than possible with sequential
    - a weather forecast that is late is useless
  - could come from
    - more processing elements (P.E.)
    - more memory (or cache)
    - more disks
- Cost: cheaper to buy many smaller machines
  - this is only recently true due to
    - VLSI
    - commodity parts

What Does a Parallel Computer Look Like?

- Hardware
  - processors
  - communication
  - memory
  - coordination

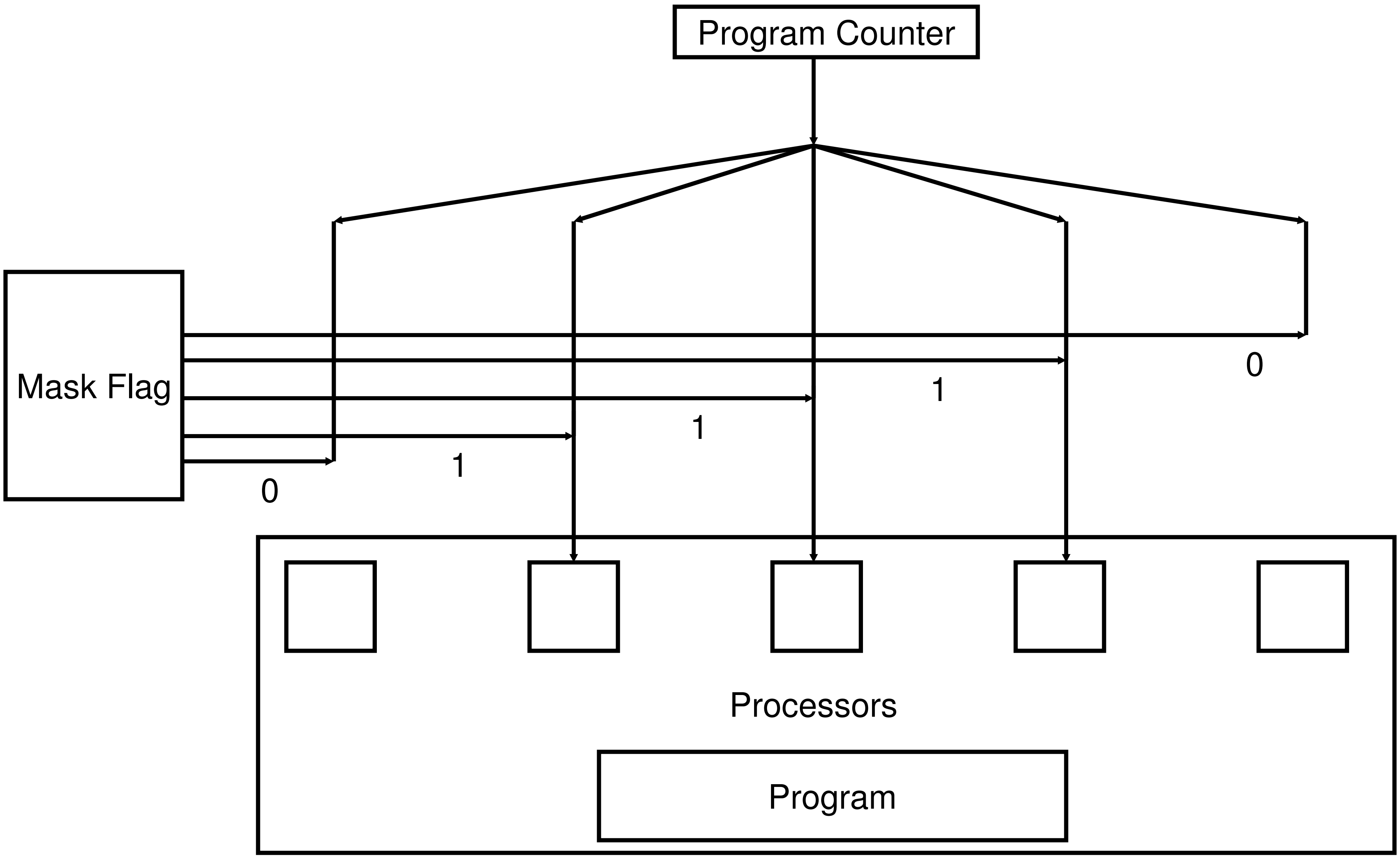
- Software
  - programming model
  - communication libraries
  - operating system

Processing Elements (PE)

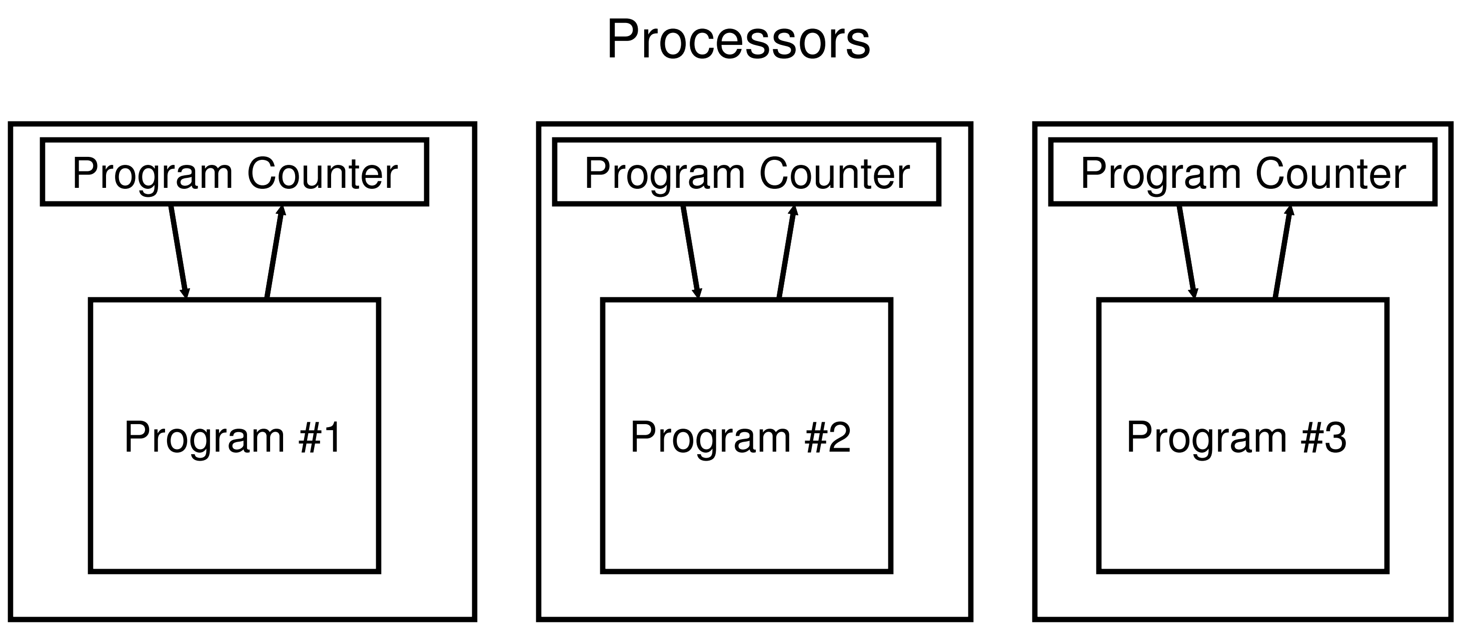
- Key Processor Choices
  - How many?
  - How powerful?
  - Custom or off-the-shelf?

- Major Styles of Parallel Computing
  - SIMD - Single Instruction Multiple Data
    - one master program counter (PC)
  - MIMD - Multiple Instruction Multiple Data
    - separate code for each processor
  - SPMD - Single Program Multiple Data
    - same code on each processor, separate PC's on each
  - Dataflow - instruction waits for operands
    - "automatically" finds parallelism

SIMD

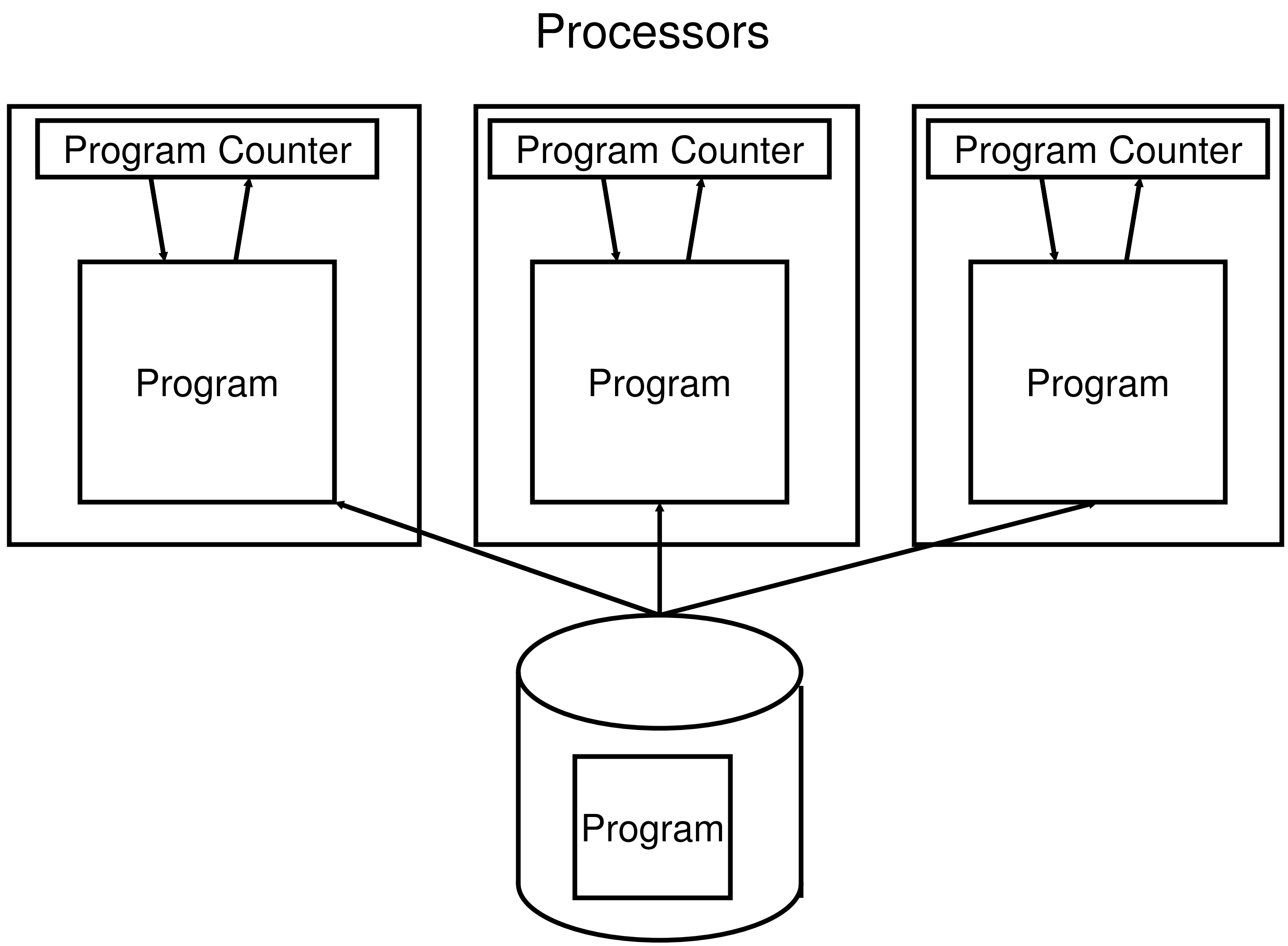


MIMD



Processors
Program Counter
Program #1
Program Counter
Program #2
Program Counter
Program #3

SPMD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Program
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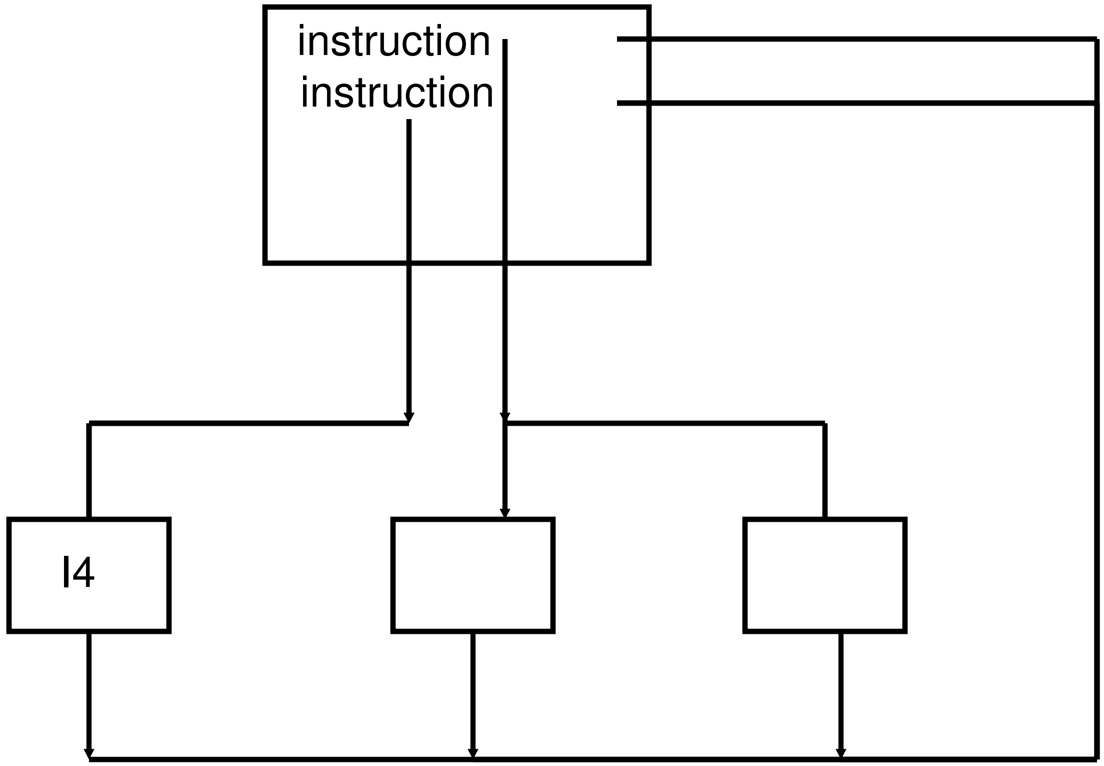
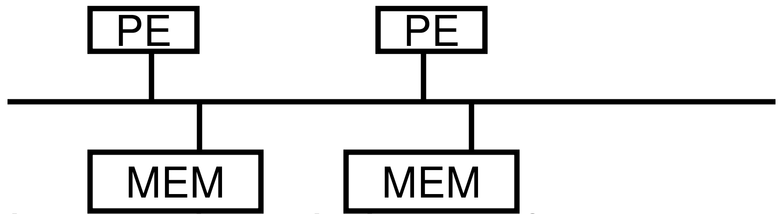
Program

Dataflow

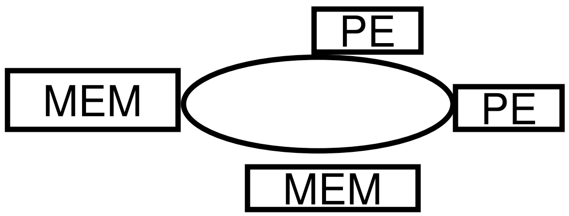


Communication Networks

- Connect
  - PE's, memory, I/O
- Key Performance Issues
  - latency: time for first byte
  - throughput: average bytes/second
- Possible Topologies
  - bus - simple, but doesn't scale

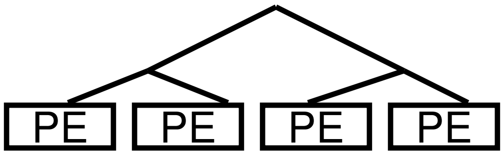


  - ring - orders delivery of messages

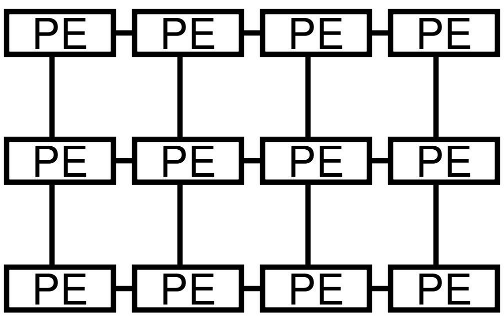


Topologies (cont)

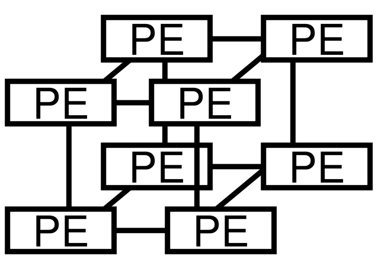
– tree - needs to increase bandwidth near the top



–mesh - two or three dimensions



–hypercube - needs a power of number of nodes



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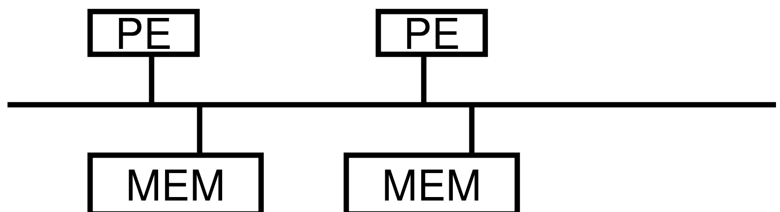

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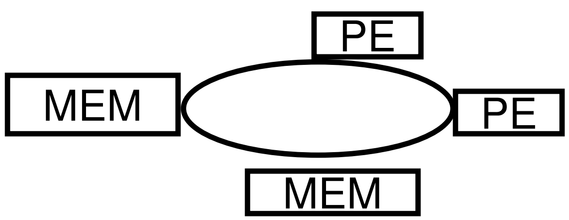

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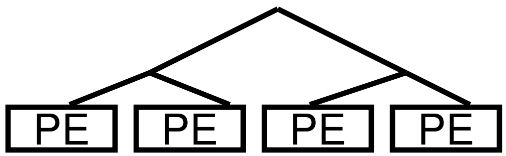

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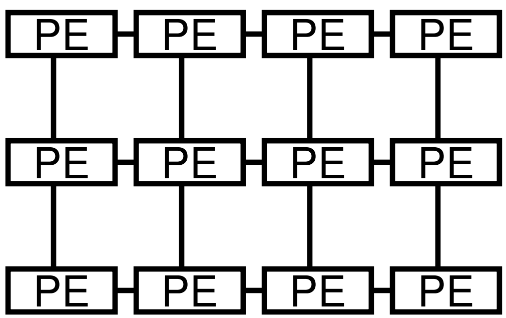

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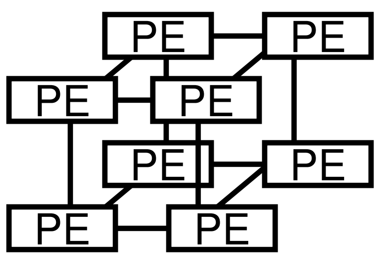

Memory Systems

- Key Performance Issues
  - latency: time for first byte
  - throughput: average bytes/second
- Design Issues
  - Where is the memory
    - divided among each node
    - centrally located (on communication network)
  - Access by processors
    - can all processors get to all memory?
    - is the access time uniform?

Coordination

- Synchronization
  - protection of a single object (locks)
  - coordination of processors (barriers)
- Size of a unit of work by a processor
  - need to manage two issues
    - load balance - processors have equal work
    - coordination overhead - communication and sync.
  - often called “grain” size - large grain vs. fine grain

Sources of Parallelism

- Statements
  - called “control parallel”
  - can perform a series of steps in parallel
- Loops
  - called “data parallel”
  - most common source of parallelism
  - each processor gets one (or more) iterations to perform

Example of Parallelism

- Easy (embarrassingly parallel)
  - multiple independent jobs (i.e..., different simulations)
- Scientific
  - Largest users of parallel computing
  - dense linear algebra (divide up matrix)
  - physical system simulations (divide physical space)
- Databases
  - biggest commerical success of parallel computing (divide tuples)
    - exploits semantics of relational calculus
- AI
  - search problems (divide search space)
  - pattern recognition and image processing (divide image)

Metrics in Application Performance

- Speedup (often call strong scaling)
  - ratio of time on n nodes to time on a single node
  - hold problem size fixed
  - should really compare to best serial time
  - goal is linear speedup
  - super-linear speedup is possible due to:
    - adding more memory
    - search problems
- Weak Scaling (also called Iso-Speedup)
  - scale data size up with number of nodes
  - goal is a flat horizontal curve
- Amdahl's Law
  - max speedup is 1/(serial fraction of time)
- Computation to Communication Ratio
  - goal is to maximize this ratio

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How to Write Parallel Programs

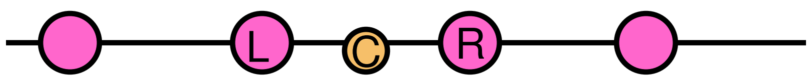
- Use old serial code
  - compiler converts it to parallel
  - called the dusty deck problem
- Serial Language plus Communication Library
  - no compiler changes required!
  - PVM and MPI use this approach
- New language for parallel computing
  - requires all code to be re-written
  - hard to create a language that provides performance on different platforms
- Hybrid Approach
  - HPF - add data distribution commands to code
  - add parallel loops and synchronization operations

Application Example - Weather

- Typical of many scientific codes
  - computes results for three dimensional space
  - compute results at multiple time steps
  - uses equations to describe physics/chemistry of the problem
  - grids are used to discretize continuous space
    - granularity of grids is important to speed/accuracy
- Simplifications (for example, not in real code)
  - earth is flat (no mountains)
  - earth is round (poles are really flat, earth buldges at equator)
  - second order properties

Grid Points

- Divide Continuous space into discrete parts
  - for this code, grid size is fixed and uniform
    - possible to change grid size or use multiple grids
  - use three grids
    - two for latitude and longitude
    - one for elevation
    - Total of M * N * L points
- Design Choice: where is the grid point?
  - left, right, or center of the grid



  - in multiple dimensions this multiples:
    - for 3 dimensions have 27 possible points

Variables

- One dimensional
  - m - geo-potential (gravitational effects)
- Two dimensional
  - pi - “shifted” surface pressure
  - sigmadot - vertical component of the wind velocity
- Three dimensional (primary variables)
  - <u,v> - wind velocity/direction vector
  - T - temperature
  - q - specific humidity
  - p - pressure
- Not included
  - clouds
  - precipitation
  - can be derived from others

Serial Computation

- Convert equations to discrete form
- Update from time t to t + delta t

```
foreach longitude, latitude, altitude
    ustar[i,j,k] = n * pi[i,j] * u[i,j,k]
    vstar[i,j,k] = m[j] * pi[i,j] * v[i,j,k]
    sdot[i,j,k] = pi[i,j] * sigmadot[i,j]
end
foreach longitude, latitude, altitude
    D = 4 * ((ustar[i,j,k] + ustar[i-1,j,k]) * (q[i,j,k] + q[i-1,j,k]) +
            terms in {i,j,k}{+,-}{1,2}
    piq[i,j,k] = piq[i,j,k] + D * delat
    similar terms for piu, piv, piT, and pi
end
foreach longitude, latitude, altitude
    q[i,j,k] = piq[i,j,k]/pi[i,j,k]
    u[i,j,k] = piu[i,j,k]/pi[i,j,k]
    v[i,j,k] = piv[i,j,k]/pi[i,j,k]
    T[i,j,k] = piT[i,j,k]/pi[i,j,k]
end
```

Shared Memory Version

- in each loop nest, iterations are independent
- use a parallel for-loop for each loop nest
- synchronize (barrier) after each loop nest
  - this is overly conservative, but works
  - could use a single sync variable per item, but would incur excessive overhead
- potential parallelism is M * N * L
- private variables: D, i, j, k
- Advantages of shared memory
  - easier to get something working (ignoring performance)
- Hard to debug
  - other processors can modify shared data

Distributed Memory Weather

- decompose data to specific processors
  - assign a cube to each processor
    - maximize volume to surface ratio
    - minimizes communication/computation ratio
  - called a <block,block,block> distribution
- need to communicate {i,j,k}{+,-}{1,2} terms at boundaries
  - use send/receive to move the data
  - no need for barriers, send/receive operations provide sync
    - sends earlier in computation too hide communication time
- Advantages
  - easier to debug?
  - consider data locality explicitly with data decomposition
- Problems
  - harder to get the code running

Ensuring a fair speedup

- T_{serial} = faster of
  - best known serial algorithm
  - simulation of parallel computation
    - use parallel algorithm
    - run all processes on one processor
  - parallel algorithm run on one processor
- If it appears to be super-linear
  - check for memory hierarchy
    - increased cache or real memory may be reason
  - verify order operations is the same in parallel and serial cases